

**Advanced Satellite-Derived Wind Observations, Assimilation,
and Targeting Strategies during TCS-08 for Developing
Improved Operational Analysis and Prediction of
Western Pacific Tropical Cyclones**

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LONG-TERM GOALS

Forecasts of tropical cyclone (TC) formation and intensity change in the north-western Pacific basin are often lacking in skill, in part due to the paucity of conventional oceanic observations that are assimilated into the operational models. This lack of observations has also constrained our understanding of how TC formation is governed by environmental processes. Recently, remotely-sensed observations from satellites have become a routine and important input to the global data assimilation systems. These data can provide critical environmental data for the testing of hypotheses of TC formation and development, and improving our understanding of how environmental influences on TC structure evolve up to landfall or extratropical transition. In particular, winds derived from geostationary satellites have been shown to be an important component of the observing system in reducing TC model track forecasts. However, in regards to TC formation, intensity change, and extratropical transition, it is clear that a dedicated research effort is needed to optimize the satellite data processing strategies, assimilation, and applications to better understand the behavior of the near-storm environmental flow fields during these evolutionary TC stages. To our knowledge, this project represents the first time anyone has tried to evaluate the impact of targeted *satellite* data on TC forecasts using an automated dynamic targeted observing strategy. TCS-08 afforded us the opportunity to employ specially-processed satellite data along with observations collected in situ by the NAVY P-3, and other platforms, to investigate these objectives as they apply in the western north Pacific TC basin. The development of successful real-time strategies to optimally assimilate wind data from

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satellites will ultimately lead to the provision of improved initial and boundary conditions for the Navy's envisioned mesoscale coupled ocean-wave-atmosphere forecast model.

OBJECTIVES

The ultimate objective of this project is the development and refinement of a capability to supplement the contemporary atmospheric observation network with advanced satellite wind observations to improve high-resolution operational analyses and medium-range forecasts of western North Pacific typhoons.

One primary research goal is to evaluate and diagnose the impact of assimilating the advanced satellite wind observations on global Navy model forecasts, and high-resolution forecasts of structure change. We aim to better understand how to utilize the satellite wind data in the context of numerical model assimilation and forecast impact. Optimizing the assimilation of the experimental satellite winds will involve a continued investigation of the satellite data impacts with respect to objective targeting of analysis-sensitive regions, and utilizing 4DVAR approaches.

APPROACH

During the field phase of TCS-08, experimental satellite-derived wind observations were produced by UW-CIMSS using state-of-the-art automated methods. Hourly datasets were routinely derived from operational images provided from the Japan Meteorological Agency (JMA) MTSAT geostationary satellite. In addition, special rapid-scan (r/s) images from MTSAT-2 were provided by JMA for extended periods (24-48hrs) over specific regions, and including parts of selected typhoon life cycles. UW-CIMSS also processed these images into wind fields (higher resolution). These special satellite-derived wind observations complemented those data collected by the NRL P-3 aircraft during TCS-08, by providing unique time-continuous environmental data in locations that were deemed important to tropical cyclone formation and development.

The project uses the latest versions of the NRL Atmospheric Variational Data Assimilation System – Accelerated Representer (NAVDAS-AR) and NOGAPS, the Navy's current operational data assimilation and global forecast model systems, so that the research results may be easily transitioned to improve the Navy's operational predictions. We expect that the NAVDAS 4DVAR assimilation will provide an improved analysis, since its temporal continuity better exploits the synoptic satellite winds than 3DVAR, in which the observations are assimilated at discrete 6-hour intervals. Upon completion of the experiments, the resulting global analyses and forecasts will be made available to investigators involved in developing and testing the Navy's coupled ocean-wave-atmosphere model.

Existing adaptive observing strategies such as the Ensemble Transform Kalman Filter (ETKF) and NOGAPS Singular Vectors have been used to identify regions in which numerical forecasts are most likely to benefit from the assimilation of additional satellite wind data. A new 'synthetic observation ensemble' will also be devised to answer this question more directly. Via the observation sensitivity method (for forecasts up to 24h) and data denial in the Navy forecast system (for forecasts up to 5 days), the impact of assimilating targeted high-density (hourly and rapid-scan) satellite winds on global model forecasts of tropical cyclone track and high-resolution forecasts of tropical cyclone structure will be evaluated and analyzed.

Finally, a method to diagnose the effects of modifying the wind analysis on forecasts of tropical cyclone track has been designed. This framework, designed using the Weather Research and Forecasting (WRF) model, can be extended for use in the COAMPS-TC framework at the Naval Research Laboratory, Monterey, and can be used to diagnose the effects of environmental perturbations on tropical cyclone intensity and structure.

WORK COMPLETED

In Year 4, the UW-CIMSS team collaborated with scientists at NRL-MRY to finish up data impact studies using the specially processed AMV datasets (hourly and special rapid-scan) produced from MTSAT by CIMSS, as described in previous reports. A series of experiments to quantify the impact of the MTSAT AMVs during TCS-08 have been performed at NRL Monterey using the operational version of the NAVDAS-AR, which is a full 4-dimensional variational (4d-Var) algorithm solved in observation space with a weak constraint formulation that allows the inclusion of model error. It uses asymptotic, continuous, and single-level data more effectively than the earlier 3d-Var NAVDAS system. AMVs in NAVDAS-AR are assimilated using a “super-ob” pre-processing approach that combines raw wind observations into averages within 1° latitude-longitude prisms in 50 hPa layers. It is the super-ob increments that are then actually assimilated into NAVDAS.

Our impact studies have concluded that the hourly AMVs, enhanced with the rapid-scan AMVs when available, contribute to a significant improvement in the NOGAPS forecasts of Western North Pacific tropical cyclones during the TCS-08 period. This accomplishment is being published in a refereed journal (Berger et al., 2011), and has also resulted in operational implementation of the hourly AMVs into the FNMOC NAVDAS system.

At the University of Miami, the primary accomplishment in the past year has been the completion and publication of a peer-reviewed article on the sensitivity of tropical cyclone forecasts to dynamic perturbations (Komaromi et al. 2011). Unlike the strategies that are used for targeting observations, the new sensitivity technique developed here involves a direct balanced perturbation to the flow. It bypasses the need for observations and data assimilation, and is instead a diagnostic technique that can be used to offer insights into how the assimilation of targeted satellite observations may influence a forecast of a tropical cyclone. In this technique, the velocity field is perturbed in a local region at the initial time, and the flow is re-balanced to produce a new perturbed analysis. The model (WRF, in this case) is then integrated forward to provide a perturbed forecast, which is compared with the forecast from the unperturbed analysis.

In addition to this work, a paper has also been completed and published on the properties of Ensemble Transform Kalman Filter (ETKF) targeting guidance for Typhoon Sinlaku (Majumdar et al. 2011).

RESULTS

The preliminary results from the UW-NRL investigations were presented in the last annual report. In summary, for NOGAPS forecasts of length exceeding 3 days, the average error of the tropical cyclone track forecasts is reduced considerably due to the assimilation of the hourly AMVs. The same forecasts were also improved further by the inclusion of rapid-scan winds. For example, for 4-day forecasts, the average track error was reduced by ~30% when hourly winds were included, and by

~45% when both hourly and rapid-scan winds were included. Furthermore, the number of forecasts of very large error, which may be considered “busts”, was reduced by the assimilation of AMVs and the average forecast error was reduced further when a lower weight was given to the bogus vortex used in the operational NOGAPS system.

Another way to view the impact of the AMVs in the NAVDAS/NOGAPS is shown in Fig. 1. Composite track forecasts for Typhoon Sinlaku are shown for the three primary NOGAPS experiments conducted in our study. For each numerical experiment, an average position of all forecasts initialized at 12-hourly intervals beginning 1200 UTC 10 September 2008 is plotted. Each solid circle or square corresponds to the average of all analyses and forecasts from the particular experiment, valid at a particular time. The example clearly shows the benefit of adding the AMVs to the subsequent composite NOGAPS forecast tracks of Sinlaku. It should be noted that there were considerable errors and uncertainty in the operational forecasts of Typhoon Sinlaku, which has been the primary TCS-08 case under investigation and during which MTSAT rapid-scan mode was activated for three days.

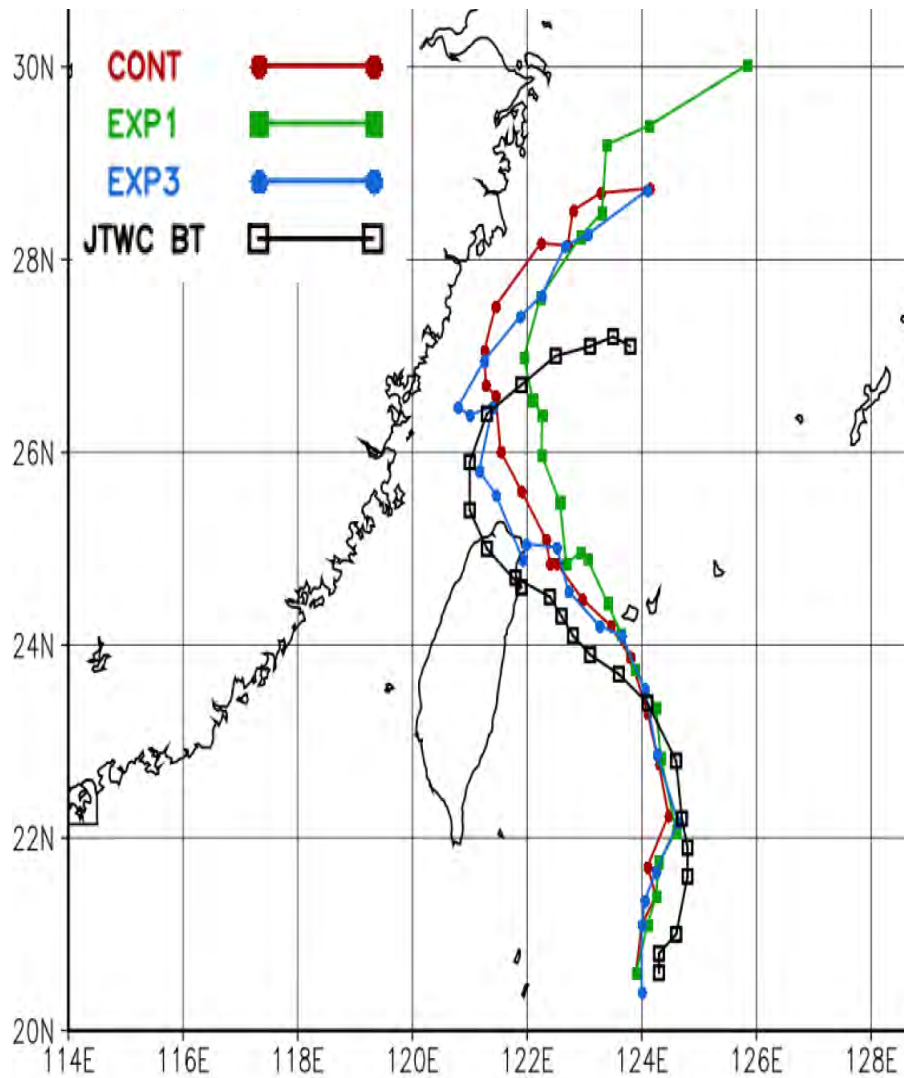


FIGURE 1. (Adapted from Berger et al. 2011): Composite track forecasts of Typhoon Sinlaku for three NOGAPS experiments: *CONT*: All operational observations including hourly AMVs. *EXP1*: Same as *CONT* but excludes all AMVs processed by CIMSS. *EXP3*: Same as *CONT* but with rapid-scan winds added between 1200 UTC 10 September 2008 and 0600 UTC 13 September 2008. For each numerical experiment, an average position of all forecasts initialized at 12-hourly intervals beginning 1200 UTC 10 September 2008 is plotted. Each solid circle or square corresponds to the average of all analyses and forecasts from the particular experiment, valid at a particular time. Note that these points vary in the number of forecasts and the forecast lengths that are provided in the composite; the points early in Sinlaku's life cycle only include short-range forecasts, whereas the points late in Sinlaku's life cycle represent a composite of 0-5 day forecasts.

The University of Miami perturbation technique has been applied to the case of Typhoon Sinlaku (Fig. 2) and Hurricane Ike, also from 2008. It was found that if the relative vorticity was reduced by 23% in the mid-latitude trough denoted by region 'S1' (Fig. 2a), the actual track of Sinlaku was almost exactly

replicated (Fig. 2c, red dot). In other words, it is hypothesized that the trough at S1 was too strong in the operational analysis, and that extra AMVs indicating a weaker trough in this region would have likely improved the forecast. Similarly, sensitivity was found in the upper-level low denoted by S2 (Fig. 2a). When the relative vorticity in this system was reduced by 25%, the forecast track of Sinlaku again resembled the actual track, out to 4 days, suggesting that the upper-level low was also too strong in the analysis (Fig. 2d, red dot). Perturbations of vorticity in other areas exhibited less sensitivity.

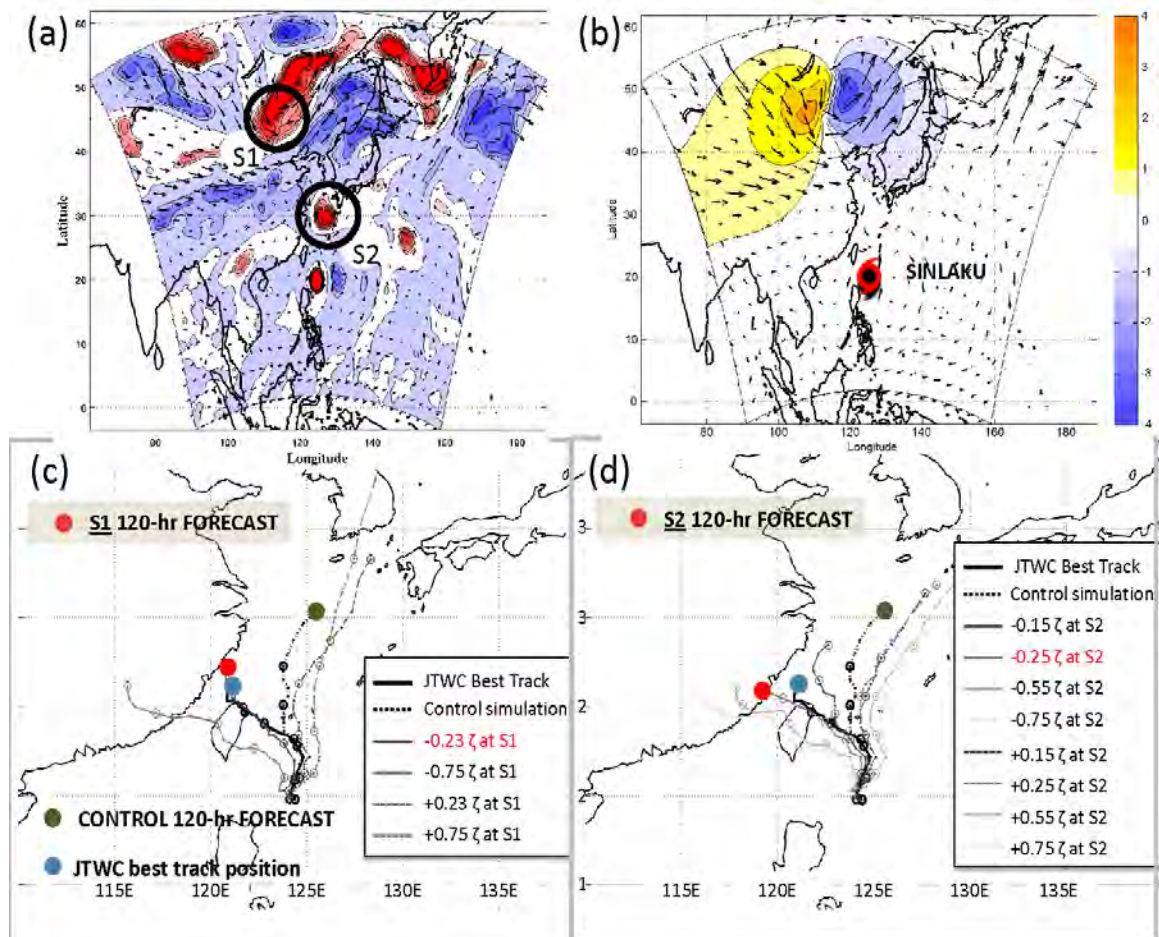


FIGURE 2. (a) *Relative vorticity (200-500 hPa layer mean) showing locations of perturbations S1 and S2 at 0000 UTC 10 September 2008, near Typhoon Sinlaku.* (b) *Perturbations of 200-850 hPa layer-mean meridional wind associated with perturbation S1, corresponding to a weakening of the trough at S1.* (c) *5-day WRF forecasts of the track of Sinlaku, integrated from four perturbed initial conditions in which the relative vorticity was strengthened (+) or weakened (-) at location S1.* (d) *As for (c), for 8 forecasts integrated from initial conditions in which the vorticity at S2 is perturbed.*

In the coming year, this technique and related tools will be applied to diagnose the dynamical and physical mechanisms that explain how the assimilation of targeted wind data modify and improve NOGAPS analyses and forecasts. For example, do the extra AMVs act to correct the amplitude and phase of nearby ridges and troughs, and/or the upper-level outflow around the tropical cyclone?

IMPACT/APPLICATIONS

A quantitative understanding of the influence of improved representations of the synoptic environment and outflow in the tropical cyclone will lead to new scientific conclusions on environmental interactions and modifications to tropical cyclone track and structure. The longer-term impact will be derived from the improved assimilation of targeted satellite wind observations in Navy (and other) models.

RELATED PROJECTS

This project is related to that funded by the TCS-08 grant N000140810250: “Using NOGAPS Singular Vectors to Diagnose Large-Scales on Tropical Cyclogenesis” (PI Majumdar; Co-PIs Peng and Reynolds of NRL Monterey). A supplement to the budget on that grant has enabled the further development of the WRF vortex initialization and inversion software for easy use by students and collaborators. This software is also being tested in the NOPP collaboration between Velden and Majumdar cited below.

This project is also related to that funded by NOPP grant N00014-10-1-0123: “Achieving Superior Tropical Cyclone Intensity Forecasts by Improving the Assimilation of High-Resolution Satellite Data into Mesoscale Prediction Models” (PIs Velden and Majumdar, Co-PIs Doyle and Hawkins of NRL-MRY).

PUBLICATIONS

Berger, H., C.S. Velden, R. Langland and C. Reynolds, 2011: Atmospheric motion vector impact on NOGAPS typhoon forecasts during TPARC/TCS-08. *Wea. & Fore.* [accepted, refereed]

Majumdar, S. J., S.-G. Chen, and C.-C. Wu, 2010: Characteristics of Ensemble Transform Kalman Filter adaptive sampling guidance for tropical cyclones. *Quart. J. Roy. Meteor. Soc.*, **137**, 503-520.

Komaromi, W. A., S. J. Majumdar and E. D. Rappin, 2010: Diagnosing initial condition sensitivity of Typhoon Sinlaku (2008) and Hurricane Ike (2008). *Mon. Wea. Rev.*, **139**, no. 10, 3224-3242.

HONORS/AWARDS/PRIZES

Co-PI Majumdar has been elected to the WMO THORPEX Data Assimilation and Observing Strategies Working Group.